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Five specific projects were developed during the current work period: 1) The Photon Multi-Leaf Collimator was characterized for electron beams. This considered the difference in collimation between the x-direction (rounded leaf ends) and the y-direction (divergent leaf sides). 2) The Monte Carlo code was parallelized for Utah Beowulf cluster. Twenty-five PCs were linked together to simultaneously calculate BEAM and DOSEXYZ. 3) The BEAM and DOSEXYZ modules were modified to calculate multiple beams in parallel and to display the does distributions o a dose phantom defined by Utah CT data. 4) Differences between measured and calculated dose profiles in the long axis of the MLC were resolved by a mathematical construct that modified the scattering foil segments by including a "flare" in each segment of the scattering foil. Failure of the unmodified MC code to predict the long axis profiles will be of interest to the whole community. 5) The transfer of CT data from the Utah CT to the Monte Carlo phantom was developed such that actual patient data can now be used directly in the Monte Carlo calculations. Simultaneously, multiple-angle, dual energy dose calculations were demonstrated on the Utah CT data sets. These items are significant, and keep us on track to finish the work in a timely manner.

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INTRODUCTION

Subject: Electron Arc Therapy was developed to treat extended superficial volumes within the postmastectomy chest wall. It has been extended to other superficial disease sites as well, but remains primarily a powerful technique for treating breast cancer. New mechanical devices such as the photon multileaf collimator (MLC) have become available since the inception of this technique. The primary advantages of this technique include greater dose uniformity throughout the prescribed chest wall treatment volume, reduced dose to the heart and lungs because of the ability to adjust the range of penetration of the electrons, and reduced dose to the apex of the lung compared to the typical treatment using a photon supraclavicular field. The primary limitations of this technique have been the labor-intensive nature of the preliminary planning and fabrication stages, the necessity to construct multiple shaped apertures, limitations in dose modeling for electrons, and the lack of an automated optimization tool to describe the shape of the MLC at each increment of arc.

Purpose: The current work seeks to overcome these limitations and to simultaneously improve the radiation dose distributions through introduction of Intensity Modulated Electron Radiotherapy (**IMERT**). Using methods similar to photon-based static IMRT, IMERT will define the dynamically varying shape of the electron aperture (Multileaf Collimator) as the linear accelerator gantry rotates around the patient and will set up the MLC treatment fields required to deliver the optimized dose distribution. This will refine the treatment planning process and will similarly minimize treatment time by automating the aperture selection and minimizing the need for tertiary collimation.

Scope: This work represents a unique extension of treatment planning and dose delivery tools for electron radiotherapy. Unique features include the use of the primary photon collimator for definition of the electron beam; superposition of multiple electron fields in an arc around the chest wall to treat large contiguous superficial volumes; definition of the dose distribution for long, narrow electron fields by Monte Carlo calculation; and determination of the variation in dose output versus electron MLC aperture shape and depth of isocenter. The advanced dose calculation algorithms applied to date have confirmed that shaped electron fields can be applied to electron arc therapy and that dose can be predicted accurately. These advanced algorithms will be used to evaluate treatment planning Dose Volume Histograms (DVH) comparing IMERT against other chest wall radiotherapy techniques, and will test clinical applicability. This is a prospective, evaluative, technical development study that will not involve actual treatment of patients during the period of the work. The expected advances, namely elimination of the labor-intensive secondary and tertiary cerrobend™ collimation will advance the value of this technique.

BODY

Five specific items of significant progress during the second year are listed below:

- **Characterized Multi-Leaf Collimator for electron beams**. We are applying Monte Carlo dose calculations to a task that has not previously been attempted, namely the calculation of electron doses for fields defined by the primary photon Multileaf Collimator. In doing this work, we detected a bug in the BEAM boundary checking algorithm. We attended an NRC workshop and consulted with the authors of the code on

MLC design and possible speed-ups. The result was NRC modifications to the MLC module (BEAM/DOSXYZ 2003 version) and suggestions that significantly enhanced speed (roughly factor 60). In this consultation we also defined several other differences between the constraints for photon calculations and electron calculations. These differences enable other improvements in performance of the code specifically for electrons.

Furthermore, unique differences exist between electron dose profiles in the X-direction (corresponding to the direction of leaf motion of the MLC) and the Y-direction (corresponding to the long axis of the electron arc fields). In the X-direction, the field edge is defined by the rounded end of the individual MLC leaves. However, in the Y-direction, the electron field is defined by the DIVERGENT side of the MLC leaves. Thus, there is a difference in penumbra effects between the X-direction and the Y-direction that are especially significant for electron beams. These differences depend upon the overall length and shape of the electron aperture. Several additional tests will be designed to evaluate the ability of the existing Monte Carlo code to predict these differences.

- **Parallelized Monte Carlo code on Utah Beowulf cluster**. Thanks to an institutional grant, we were able to purchase 25 PC's with processor speed between 2.2 and 2.8 GHz. These processors were configured into a Beowulf Cluster and applied to the Monte Carlo dose calculations. In order to use the code with this cluster, we designed special-purpose scripts such as **parallel_reset**, **parallel_run**, **parallel_pardoselinks**, and **combinedose**, that distribute BEAM/DOSXYZ input files over the cluster, initiate runs on each machine, and combine the results into a single output dose distribution. We developed data handling scripts and protocols for multiple machines. The resulting speed-up factor was about 25 for the current cluster. This is significant in that a dose calculation that previously took all day can now be completed in less than an hour, enabling iterative evaluation of techniques for aperture optimization. We hope to make further speed enhancements as we become more familiar with the code.

- **Implemented BEAM/DOSXYZ for multiple beams on dose phantom defined by Utah CT data**. A key element in this study will be the ability to apply the Monte Carlo dose calculations directly to CT data sets representative of actual patients who are treated using electron arc therapy. To accomplish this, we developed codes and protocols to access Utah CT data, and incorporate the data into a four-level BEAM/DOSXYZ dose phantom. We developed multiple beam parallelization scripts and naming conventions (S###_T#_P#_C#_D#), and defined the gantry angles theta (T) and phi (P), and the collimator angle (C), appropriate to Utah CT geometry. The geometry was checked using repeated calculations with a 5cm wide MLC field.

- **Designed BEAM scattering foil flare to match measured short and long axis dose profiles**. In our initial studies, the calculated dose profiles in the long dimension exhibited a 10- to 15% increase in off-axis dose. This effect is referred to as "horns" and is commonly seen in older photon linear accelerators. However, it is a spurious effect in the electron fields we are investigating. Several effects in the Monte Carlo calculations

may be contributing to this anomaly. For example, the dose calculations appear to see a "gap" above the first leaf and below the last leaf of the MLC, and generates a dose contribution through that gap. This effect was eliminated by adding a single five-cm wide leaf above the first MLC leaf and below the last MLC leaf. This had the effect of "tricking" the code into seeing additional absorption beyond the limits of the MLC. Additionally, we identified anomalies due to the finite tongue and groove model for MLC leaves. This effect was minimized by reducing the dimensions of the tongue and groove. However, the horns remained. This problem was resolved by introducing a "flare" to the individual components of the scattering foil. This mathematical construct enabled excellent agreement between measured dose profiles and Monte Carlo calculations. Alternatively, we are investigating the influence of different scattering foil thickness and different relative foil positions on the calculated beam profiles. In making these modifications to the code, we consulted with Dave Rogers of Ottawa NRC on anomalous dose effects and possible speed-ups of BEAM/DOSXYZ. Examples of these effects will be illustrated in the attached graphs. We are also consulting with experts in Monte Carlo calculation techniques to see if they can reproduce these anomalous calculation results.

Generated multiple angle, dual energy (16 and 6 MeV) dose calculation on Utah CT phantom. The end product of these studies will be optimization of dose calculations using CT data sets corresponding to actual patients. The dose calculations will be the superposition of multiple shaped electron fields at increasing gantry angle through an arc around the patient. These shaped electron fields will have energies from 6 MeV to 20 MeV as determined by the required depth of penetration into the chest wall and mediastinum. We identified and investigated input file number limits that occur in **combinedose** with multiple beams distributed over a significant number of machines (as in the Utah Beowulf cluster). This effect limits maximum particle number, and will be corrected. The 3D superposition of multiple fields and energies is illustrated in the attached figure. This clearly demonstrates the feasibility of the proposed calculation.
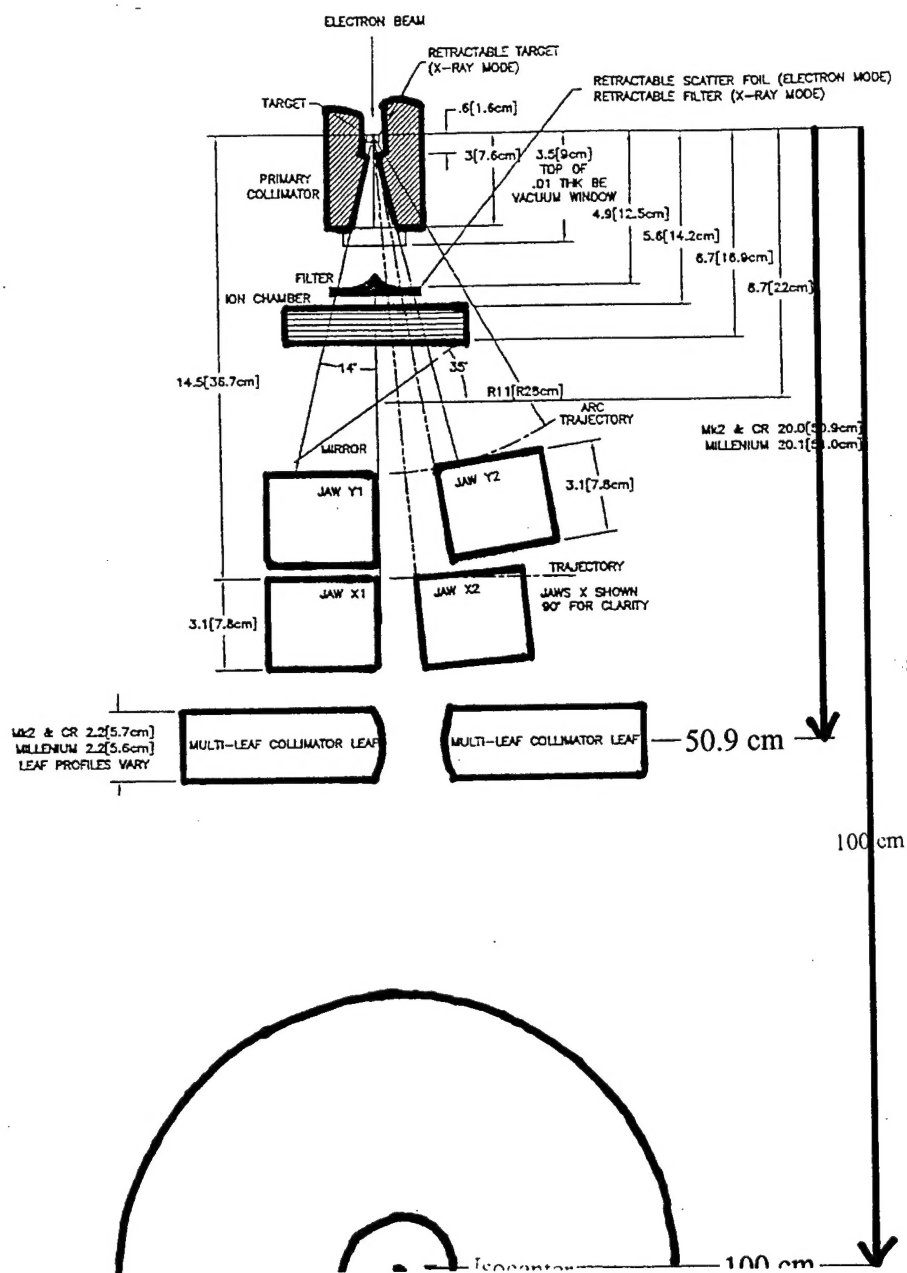
Figure 1: Schematic of Varian Clinac 2100C beam line. Critical components involved in the Monte Carlo BEAM simulation are: electron scattering foil, ionization chamber, primary photon collimators, and multi-leaf collimator. The distance from the center of the MLC (the last collimating device) to isocenter is 50 cm. Since typical patient isocenter depth ranges from 10 to 20 cm, this leaves an air gap of between 30 and 40 cm. Electron scattering within this air gap contributes significantly to the broadening, Gaussian shape of the electron arc beam profiles.
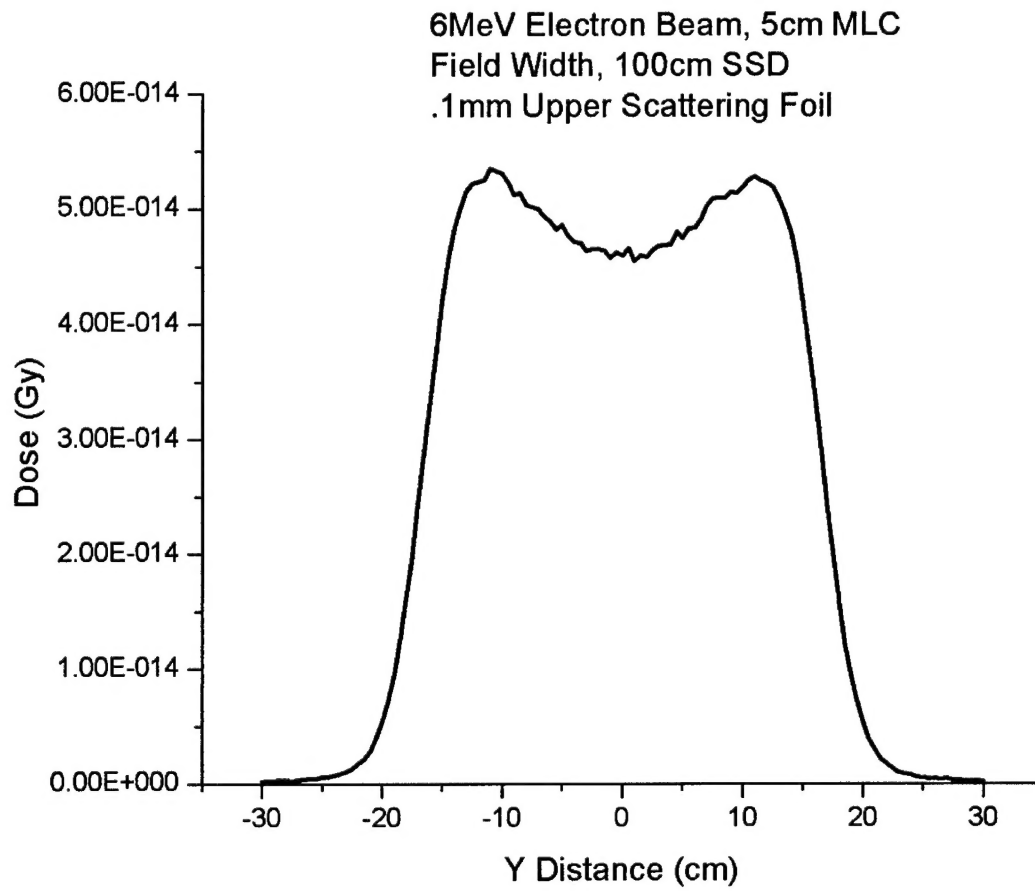
Figure 2: Long-axis profile calculated using Monte Carlo code without inclusion of flare effect on scattering foil components. Notice the horns produced by this calculation.
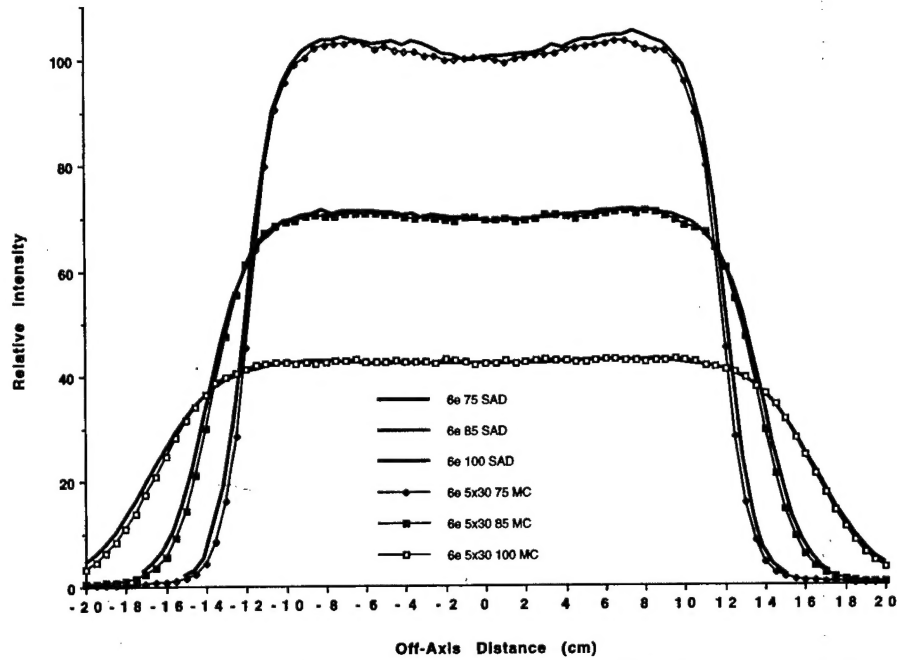
Figure 3: Long Axis Beam Profiles for 6MeV Electron Beam. Comparison of Water Phantom Measurements and Monte Carlo Calculations for 75cm, 85cm, and 100cm SSD with 5cm x 30cm MLC Field. These profiles do not exhibit the horns seen in the previous Monte Carlo calculation, since a flare is included in the description of the scattering foil components.

6 MeV Electron Arc - Profile vs. SSD
Measurement vs. Monte Carlo

Legend:
- 7 MC 75
- 7 MC 85
- 7 MC 100
- 7 wide 75 SSD
- 7 wide 85 SSD
- 7 wide 100 SSD

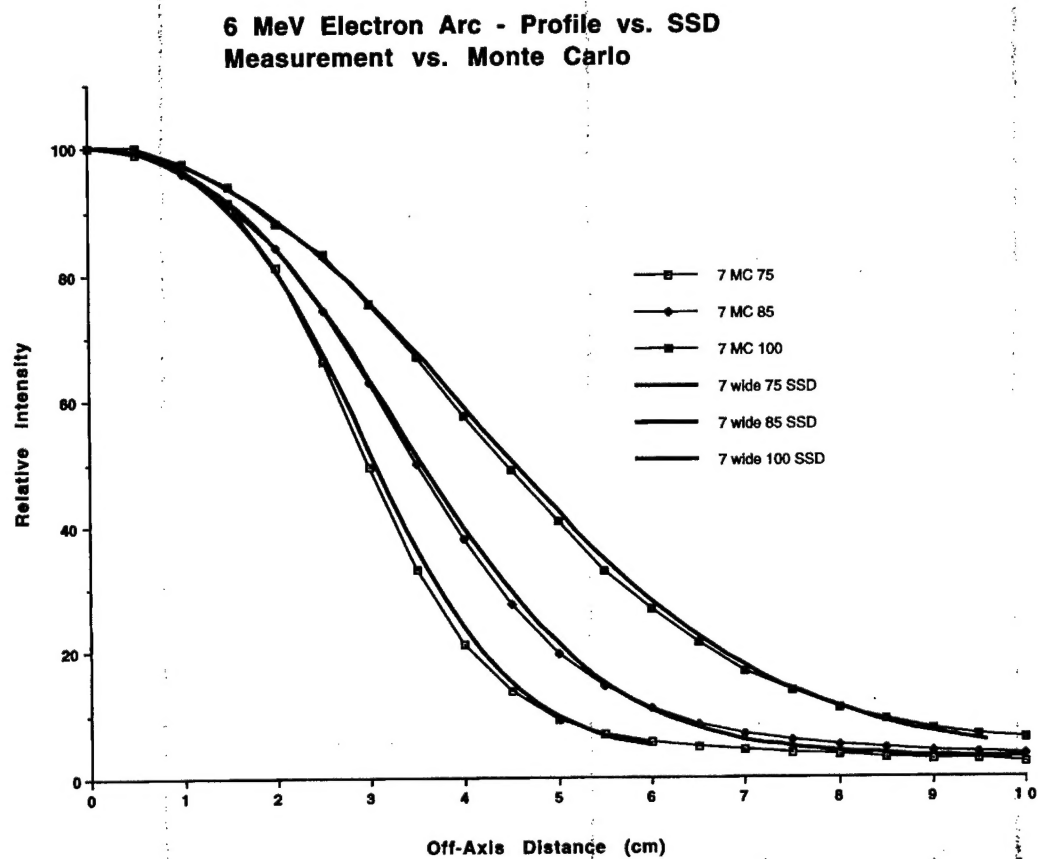Y-axis: Relative Intensity
X-axis: Off-Axis Distance (cm)

Figure 4: Short Axis Beam Profiles for 6MeV Electron Beam. Comparison of Water Phantom Measurements and Monte Carlo Calculations for 75cm, 85cm, and 100cm SSD for 7cm x 30cm MLC Field.
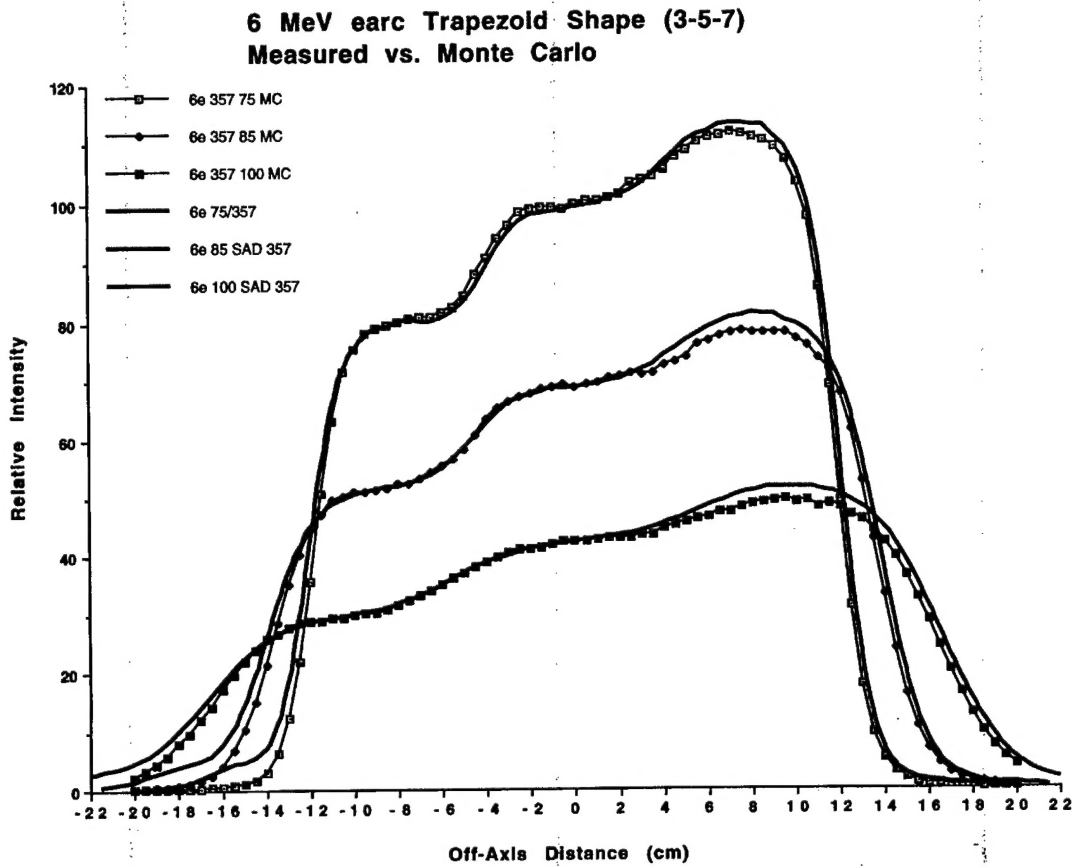
Figure 5: Long Axis Beam Profiles for 6MeV Electron Beam. Comparison of Water Phantom Measurements and Monte Carlo Calculations for 75cm, 85cm, and 100cm SSD for 3cm-5cm-7cm Trapezoid.
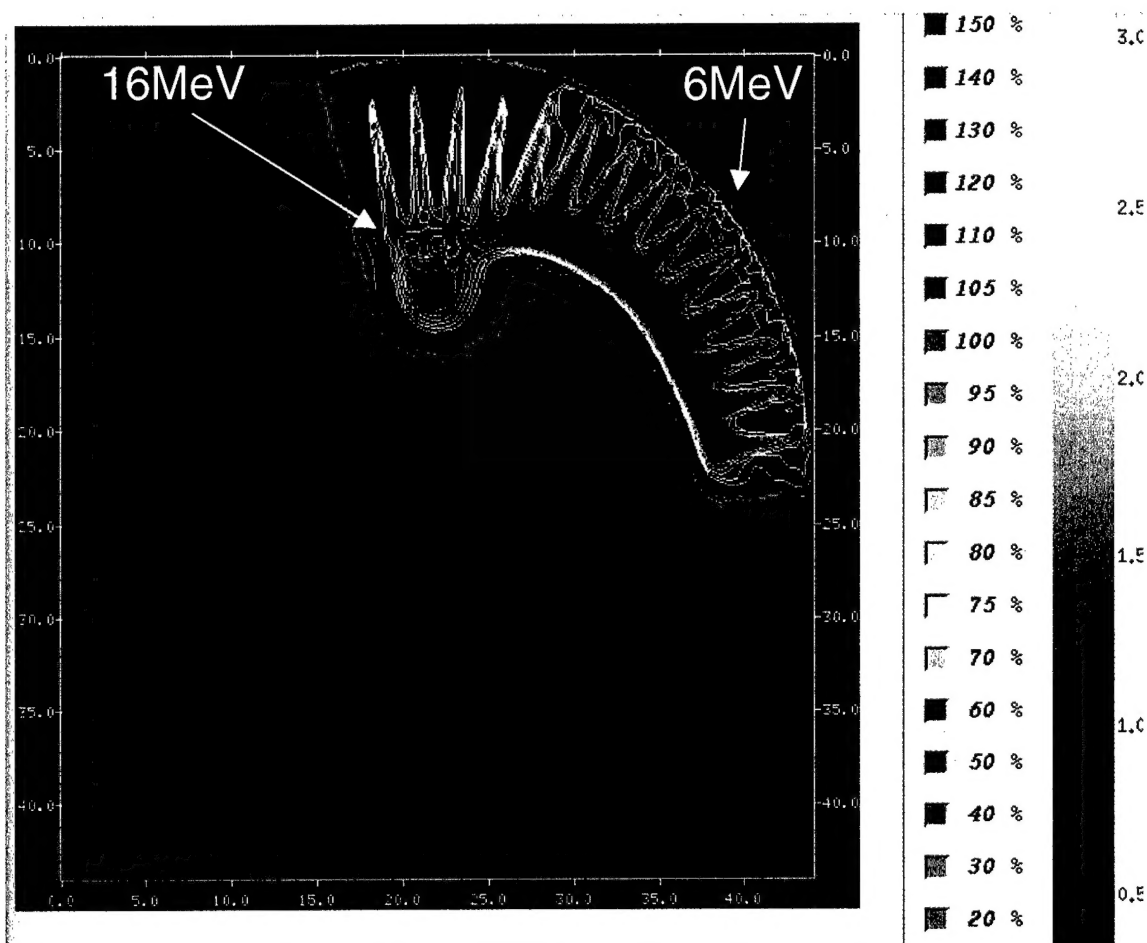
Figure 6: Monte Carlo Dose Contours on Utah CT Phantom. Single slice shown for 16MeV and 6MeV 5cm x 30cm MLC fields in Electron Beam Arc. Note the greater depth of penetration of the electron dose in the mediastinum region due to the application of 16 MeV electrons, compared to 6 MeV electrons across the chest wall. Significant points of study will be to evaluate the dose predictions to the underlying lung, compared to pencil beam electron dose calculations. The composite dose distribution is constructed as the summation of a series of fixed electron fields. In this presentation, the dose to air is included in the picture. Future illustrations will truncate the dose display to within the patient contour.

KEY RESEARCH ACCOMPLISHMENTS

- Documented anomalies in Monte Carlo dose calculations
- Implemented of Beowulf Network for distributed processing of Monte Carlo dose calculations
- Implemented entire process for treatment planning (CT data accumulation; CT transfer to Monte Carlo realm; definition of MLC-defined aperture shape; superposition of multiple fields and energies in composite electron arc dose distribution using actual patient CT data.

REPORTABLE OUTCOMES

- Oral scientific presentation at ASTRO October 2003

CONCLUSIONS

Improved performance in Monte Carlo dose calculation has been achieved by implementing a Beowulf Network of 25 PC's and by streamlining several sections of the MLC calculation code. The anomaly discovered in the long-axis profiles will be further investigated and a realistic solution developed. This will be done in conjunction with experts in Monte Carlo dose calculations. The entire chain of events that must take place in order to deliver optimized dose distributions to phantoms simulating actual patients has been verified. This sequence will be smoothed during the coming year. The work done to date keeps us "on track" to achieve a successful completion of this project within the period of the grant.

"SO WHAT SECTION": Implementation of the Monte Carlo code for calculation of doses defined by the shaped aperture of the photon MLC will increase the accuracy of dose delivery as determined by the optimization techniques. The elimination of cumbersome and labor-intensive secondary and tertiary collimation will be a major boon to electron arc therapy. And finally, automation of the MLC shapes during arc rotation will minimize the time required to treat this class of patients, and will therefore improve patient and staff satisfaction with the over-all complex procedure.